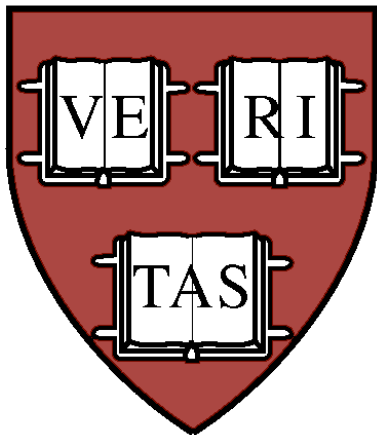# W/Z +Jets in Early LHC Data
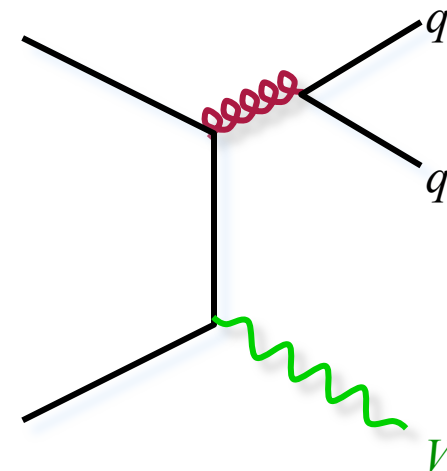
Kevin Black

Harvard University
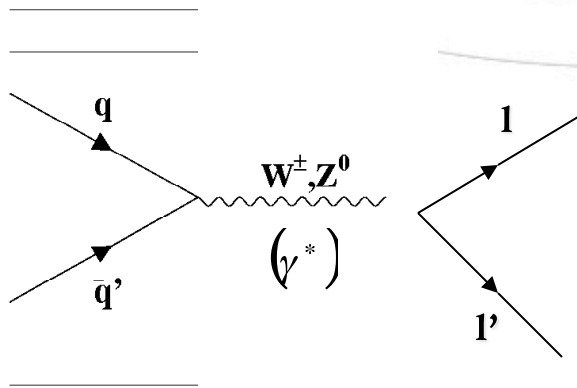
# Outline

- W/Z+ jets physics
  - Test of QCD (large $Q^2$)
  - Sensitive to Hadronization Modeling

- W/Z +jets as tool
  - Jet Energy Corrections
  - Background to 'known' physics

- W/Z +jets as discovery channel
  - Higgs, SUSY, etc…

- Prospects with 100 pb$^{-1}$
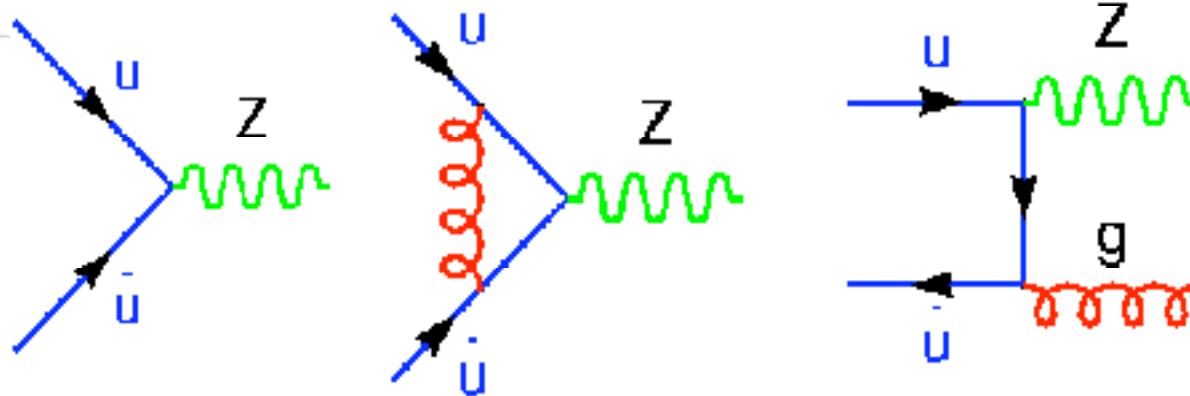
W/Z + jets

# Basics of W/Z + Jets Production

**q** **l**

$W^\pm, Z^0$

$(\gamma^*)$

**q̄'** **l'**

**kinematic variables:**

$$Q^2 = M^2$$

$$y = \frac{1}{2} \ln \frac{x_2}{x_1}$$

- W/Z production from qq annihilation
  - → $\eta$, $p_T$ distribution depend on pdf
- large dijet production at Hadron Colliders
  - → selection based on leptonic decays
    - **W → lν** (BR: 11 % per mode)
      - 1 isolated lepton, Missing ET
    - **Z → ll** (BR: 3% per mode)
      2 isolated leptons,
- Jets from gluon radiation.

# Jets via Radiation



$\mathcal{O}(\alpha)$: W/Z bosons produced with $p_T = 0$

- $p_T$ attributed to gluon radiation, expected to broaden
- with $Q^2$ : $M \approx 10$ GeV $\Rightarrow$ $\langle p_T \rangle \approx 1$ GeV
    - $M \approx 80$ GeV $\Rightarrow$ $\langle p_T \rangle \approx 5$ GeV
    - $M \approx 91$ GeV $\Rightarrow$ $\langle p_T \rangle \approx 6$ GeV
- measurements of $d\sigma/dp_T$:
  W $\rightarrow$ higher statistics, Z $\rightarrow$ better resolution

# W/Z + jets at Hadron Level

- Matrix Element Calculations at parton level

- Measurements made at observable jet (hadron) and lepton level

- Description of hard sub-process best described by matrix element calculations

- Showering (non-pertubative) relies on showering model (Pythia, Herwig, Sherpa)
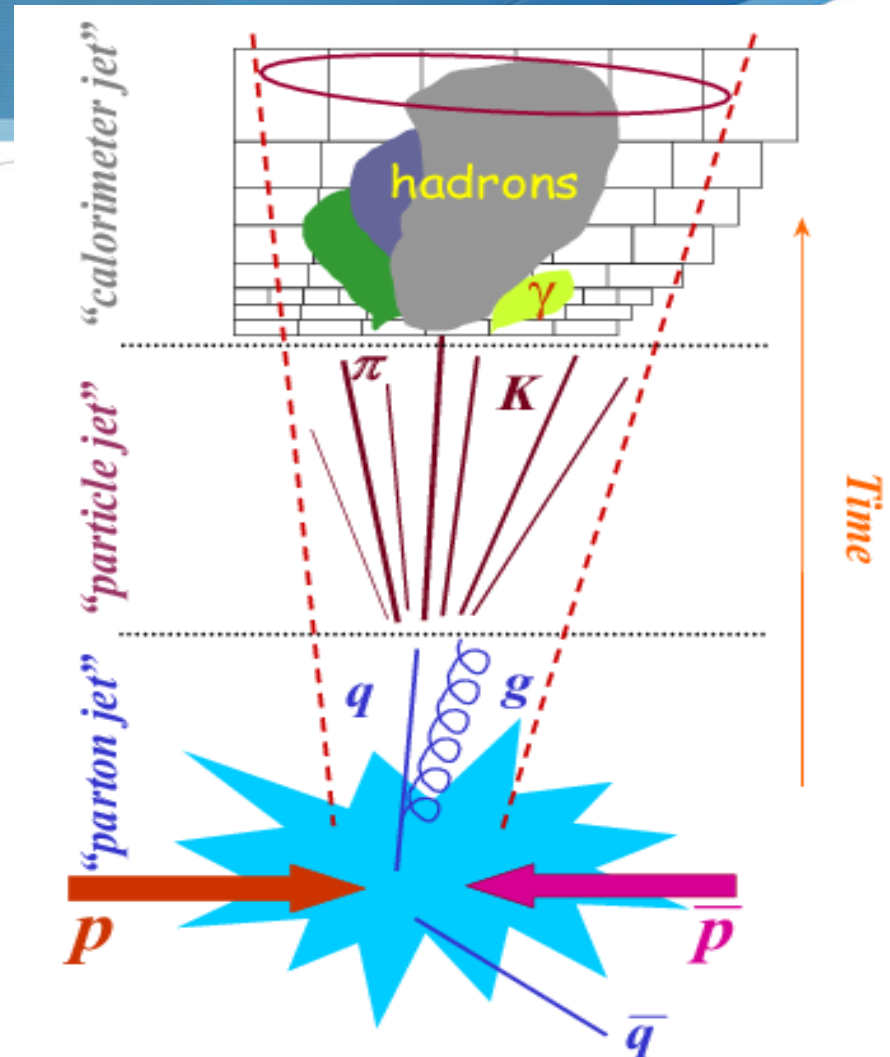
# Matching ME + showering

- Matrix element calculations available for hard emission

- Soft/Colinear Emission enters non-pertubative region
  - Pythia/Herwig/Sherpa offer models of showering tuned to data

- 'Matching' procedure to avoid double counting (from both matrix element and hadronization)

$W \rightarrow l\nu$
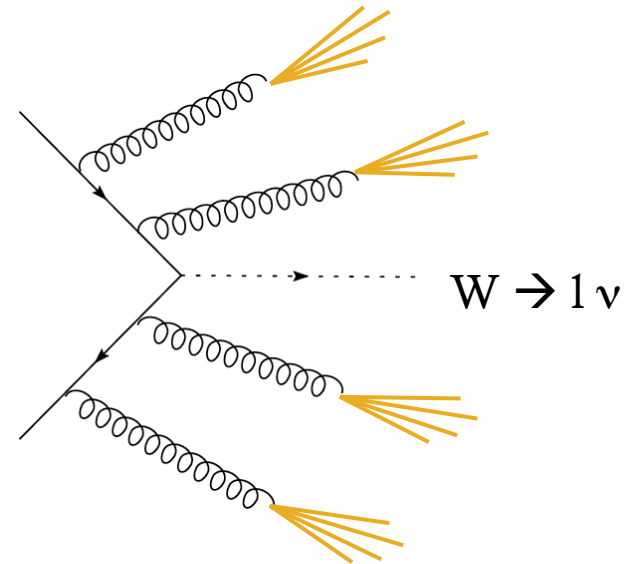
# Theoretical Status

- W/Z+Jets cross-section calculated at NNLO for up to 2 partons

- Implemented in MCFM at NLO for up to 2 partons



$$\sigma \sim \sum_{a,b} f_{a/N_1} \otimes f_{b/N_2} \otimes \hat{\sigma}_{ab}$$
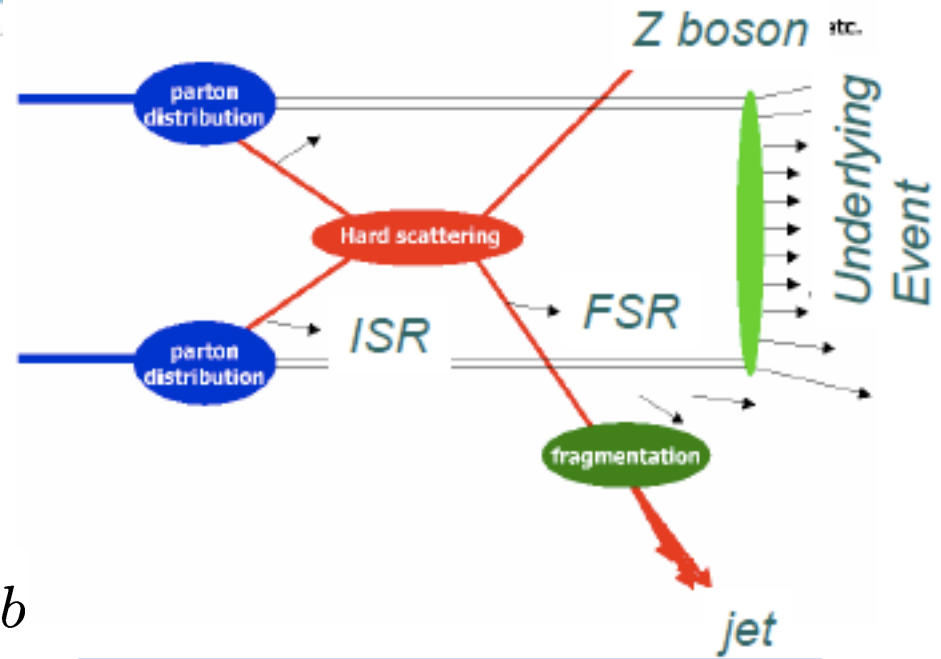
# Monte Carlo Comparisons

- MCFM/Alpgen + hadronization with Pythia

- Normalized at 0 jet bin

- As expected Pythia only prediction softer (as expected?)

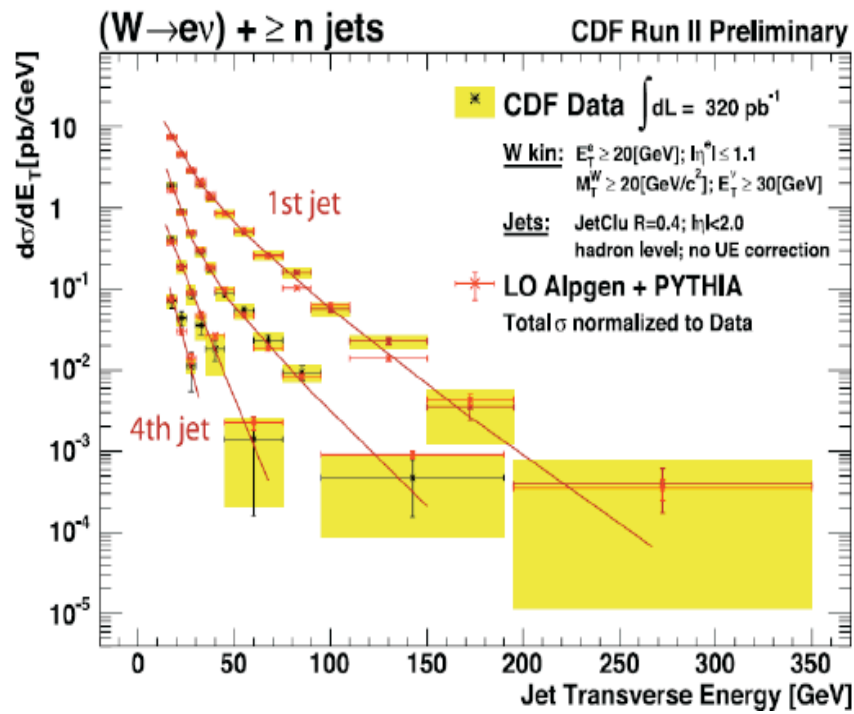- Tevatron comparisons show (for the most part) good agreement between data and MC
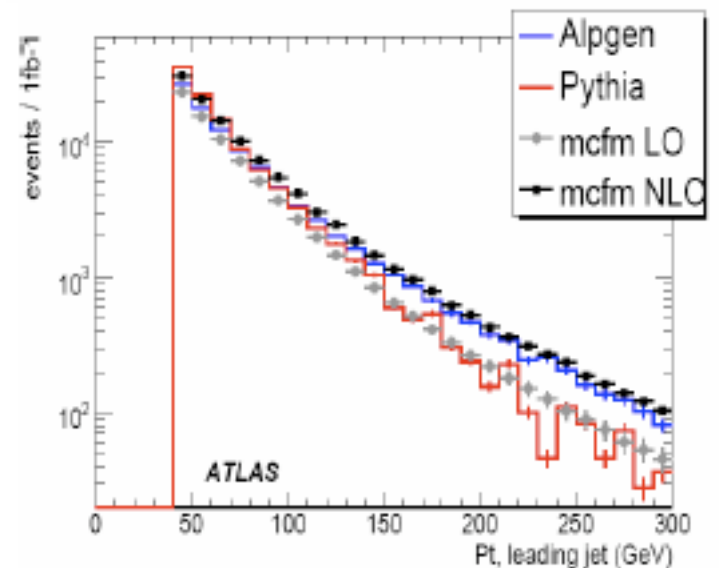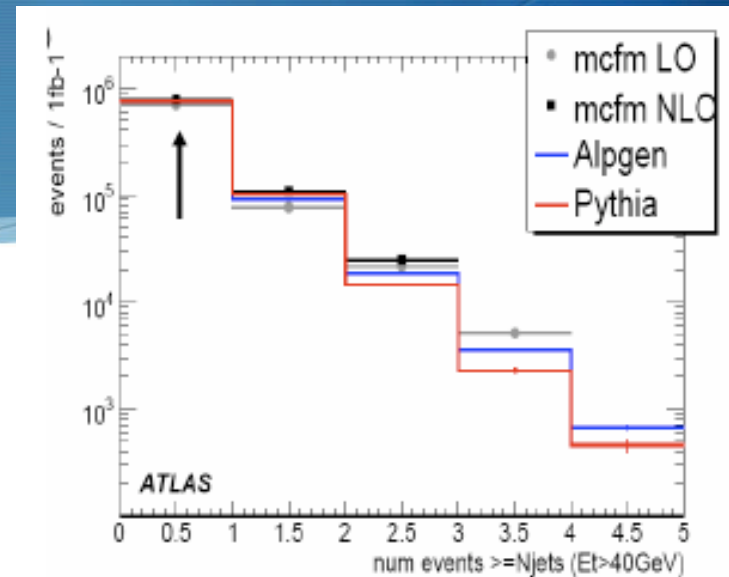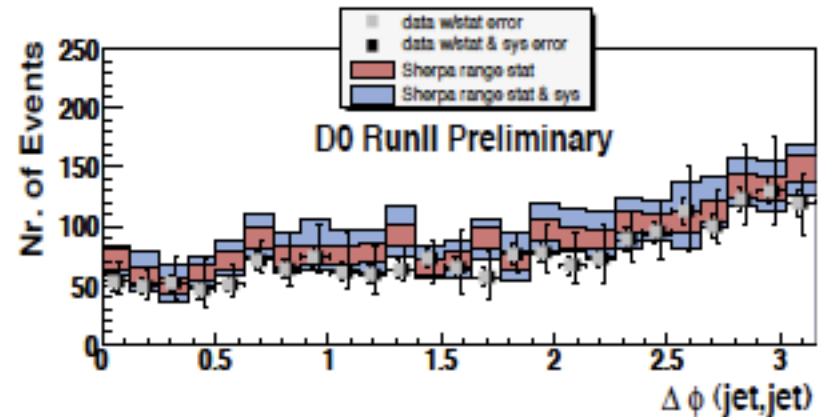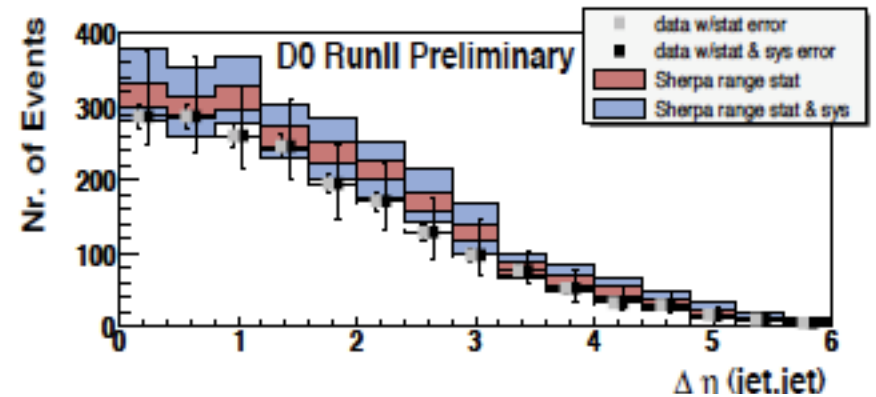
# Backgrounds



- Generally very clean (~10% background for W 2-3% for Z

- W+jets
  - W+tau,Z, Multijet, tt

- Z+jets
  - W,Z,top QCD

- Large increase (100!) in tt cross section implies it will dominate background at large jet multiplicity
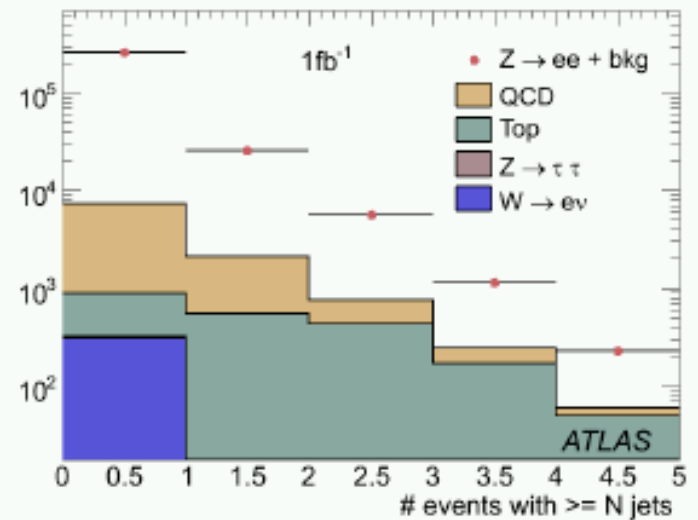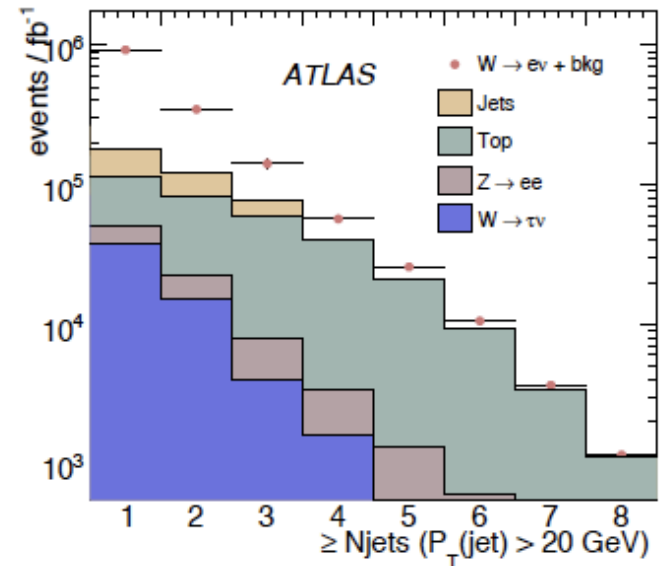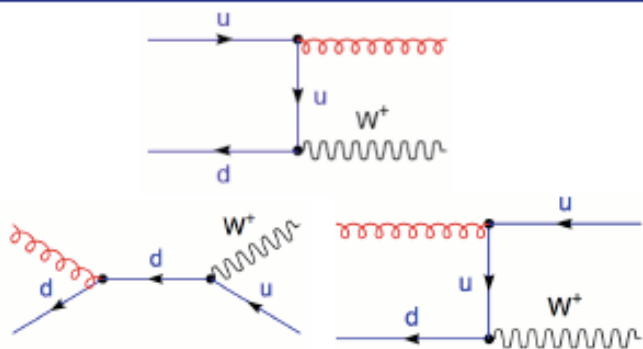
# At the Tevatron



Good agreement over several orders
Of magnitude …

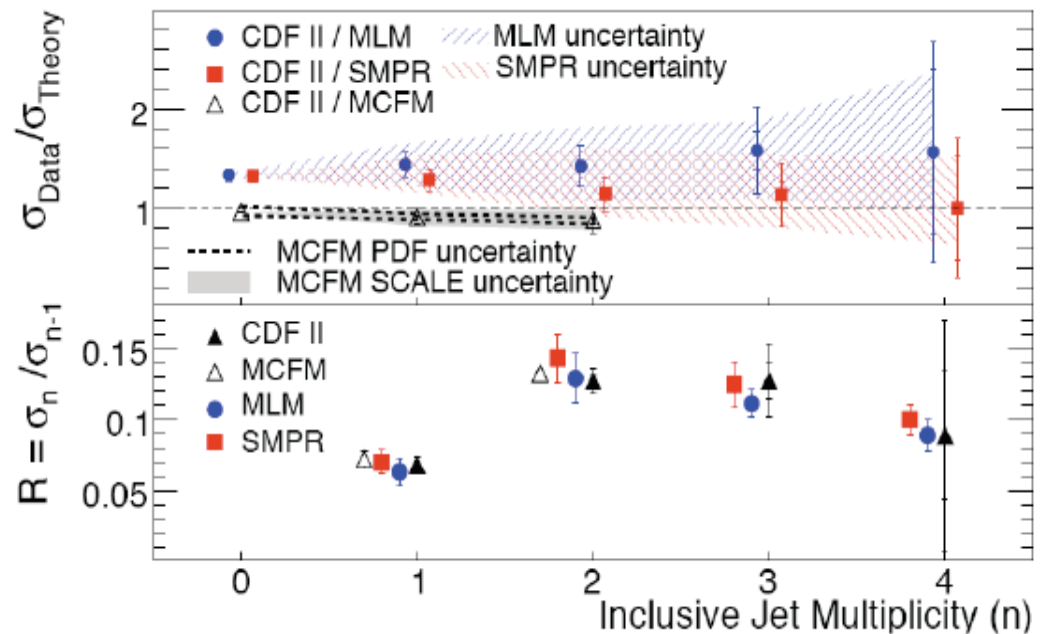Detailed shape variables well
described

# Tevatron II



CDF-II results for W +n
Jet cross-section

MLM – Alpgen
MCFM
SMPR – Madgraph

# Tests of QCD I

- At LO W/Z has 0 Pt
  - Gluon Radiation causes boson to recoil generating transverse momentum
  - High Transverse momentum results from hard gluon radiation
  - Low Transverse momentum dominated by soft multiple gluon radiation
  - resummation of large $\ln(Q^2/p_T^2)$ terms
  - $p_T \rightarrow 0$: parameterize non-perturbative contribution
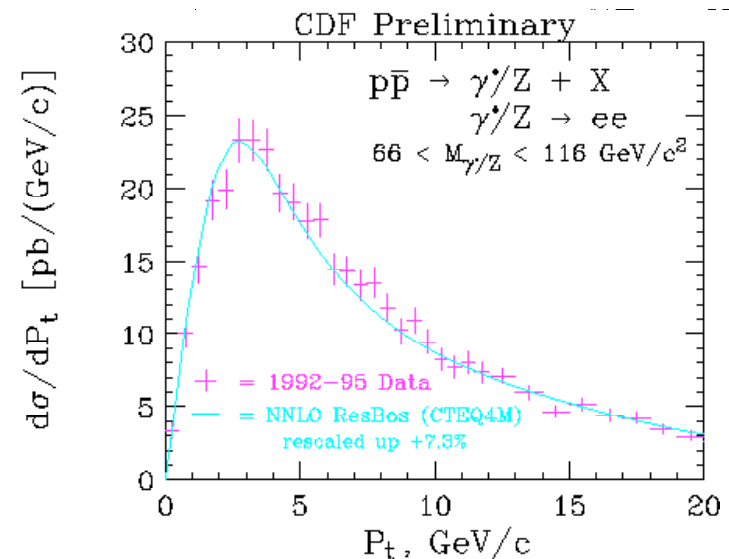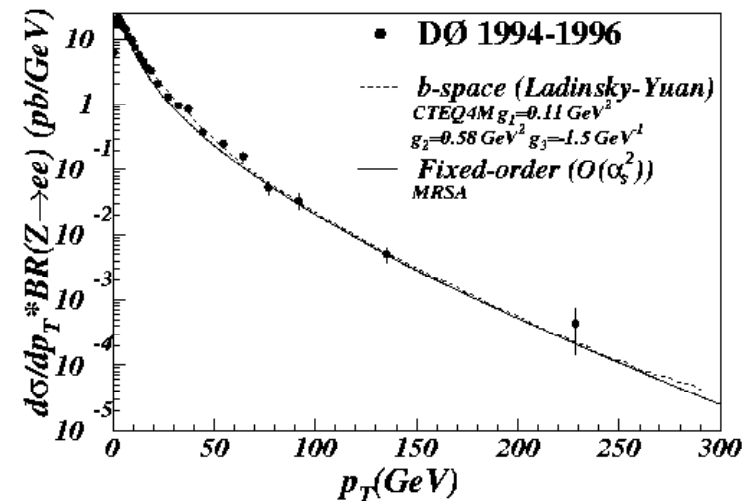
# Tests of QCD II

- W+njet  Jet pt spectrum

- Comparison to Theory
  - MLM – Alpgen Pythia
  - MCFM
  - SMPR – Madgraph
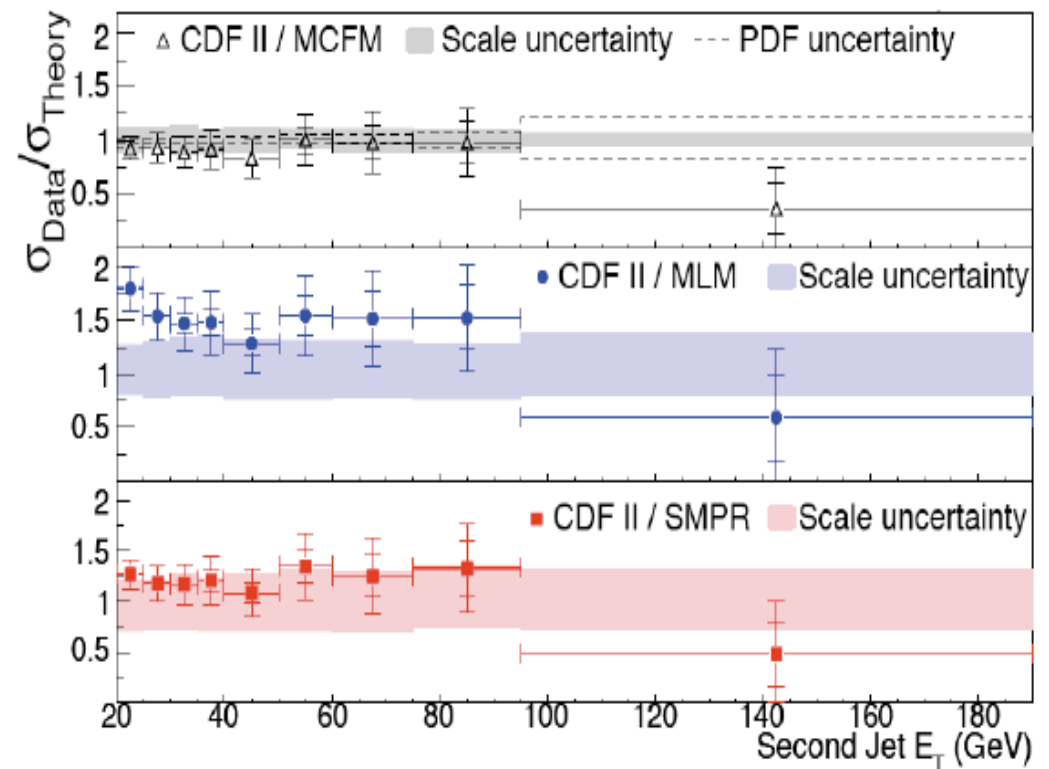
# Background For Top I

- Recall Tevatron (Run I) discovery of top

- After removal of instrumental (multijet) background the largest background is W+jets

- Prediction of 3 and 4 jet bin multiplicity bin critical

- 'Berend's' Scalling
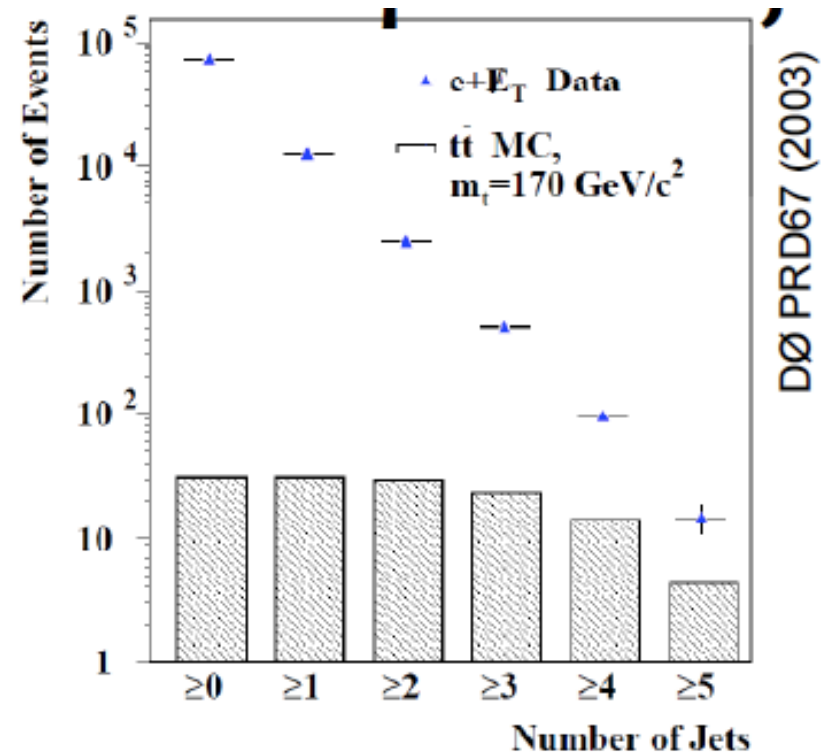
# Background for top II

- Cross-section for top increases by factor of 100 from Tevatron, W +jets increases by ~10

- Should be signal dominated

- Modeling of W+jets not as important for seeing top but rather for extracting precision properties
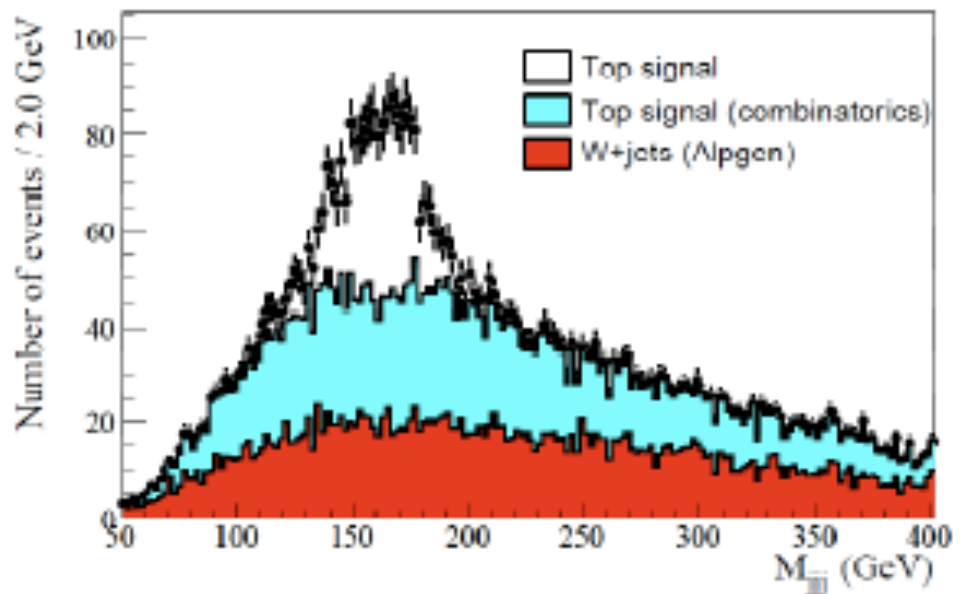
# Associated Higgs Production



- Low Mass Higgs Difficult due to branching ratio to bb

- Need to use multi channels for discovery
  - Gamma gamma
  - ttH
  - WH,ZH

- Note diphoton channel is a (very!) rare decay

- Even if discovered in diphoton channel need to see it in other channels

# Associated Higgs II

- Problem : Signal to background ratio (without cuts) is very poor ~ 1000 to 1

- Long recognized that could take advantage of boost of Higgs in gamma gamma channel

- In associated production this was not studied completely until recently (jets broader)
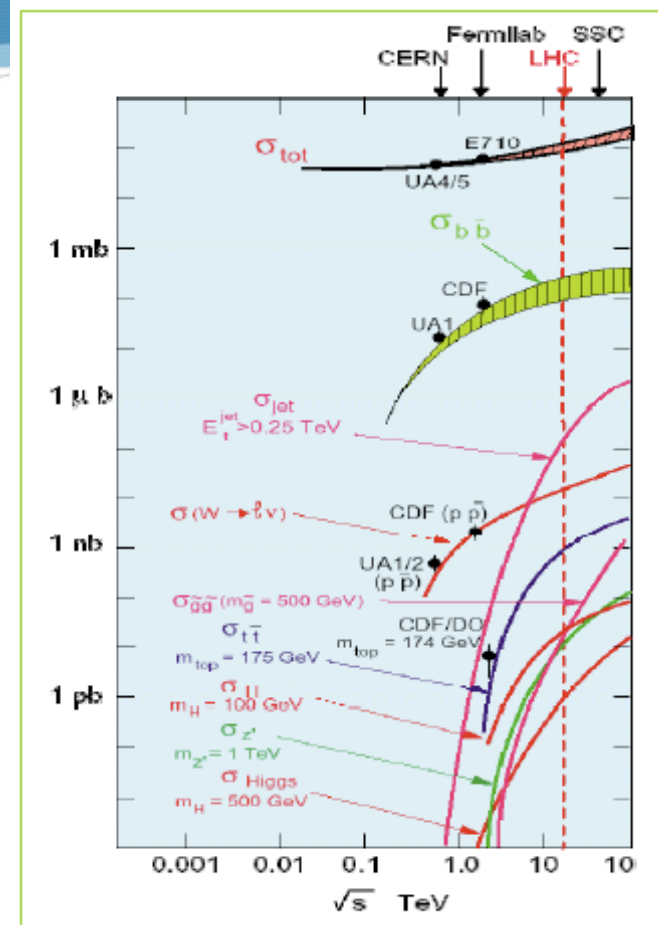
# Associated Higgs 3
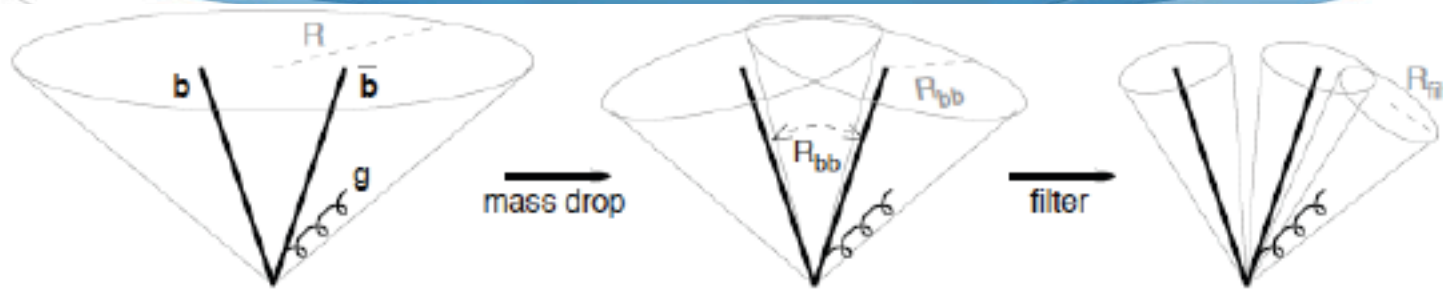


- 'Undo' last step of jet clustering algorithm to reveal substructure

- Split into 2 'subjects': if significant mass drop and not too asymetric pt split keep jets

- Repeat procedure until 3 hardest subjects are found – require two to have b-tag

# Associated Higgs Production

- Requires a lot of data (30 fb-1)

- However interesting in early data for other Zbb resonances
  - Technicolor

- Full Simulation studies ongoing…
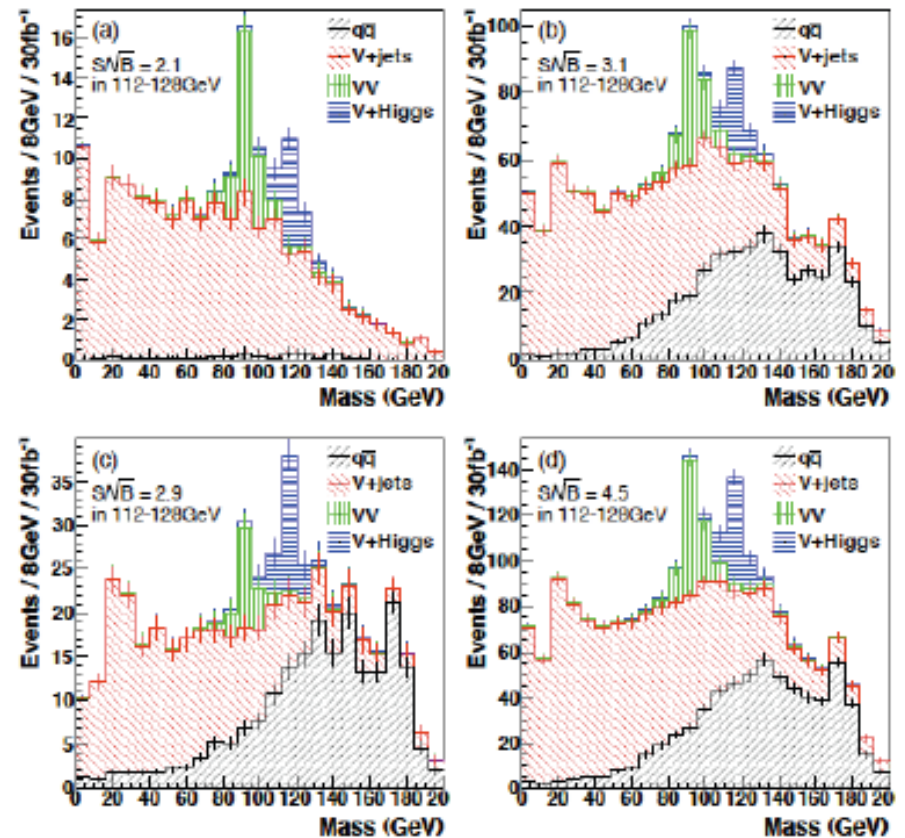
# Tool for searches

- Z->νν + Jets
  - Searches for SUSY in MET + Jets Channel

- Measure Cross-Section in dilepton+jets channel
  - Correct for acceptance
  - Unfold to get true distribution

- Form template from dilepton data to model 'invisible' decay mode shape and normalization
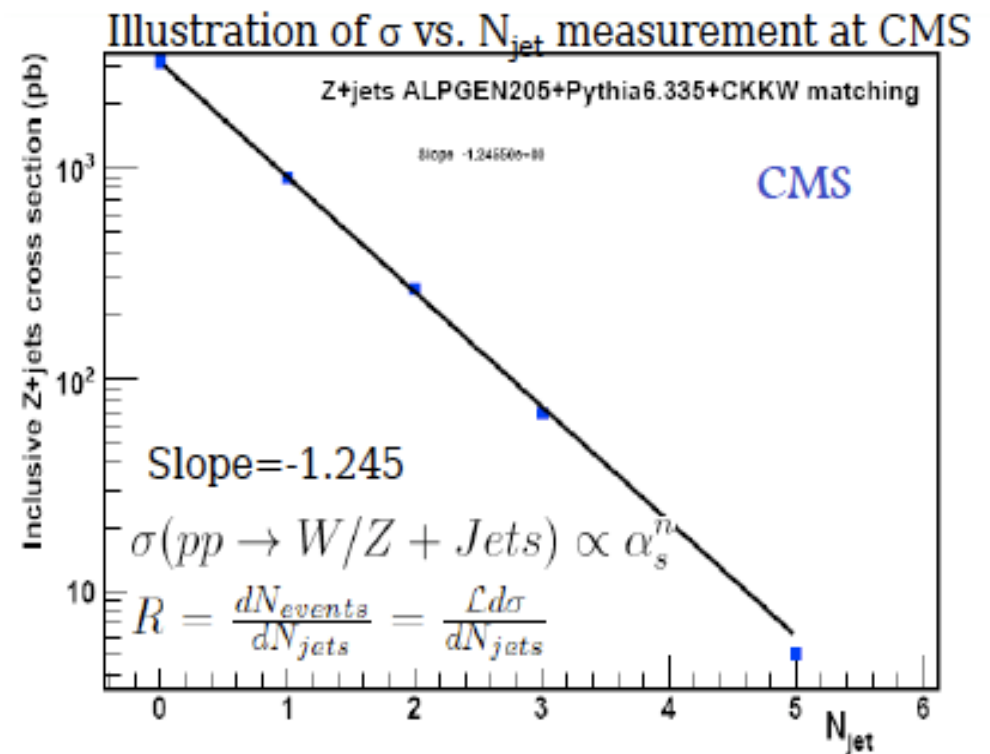


Z→ll
Z→ ν ν ("data")

MET (GeV)
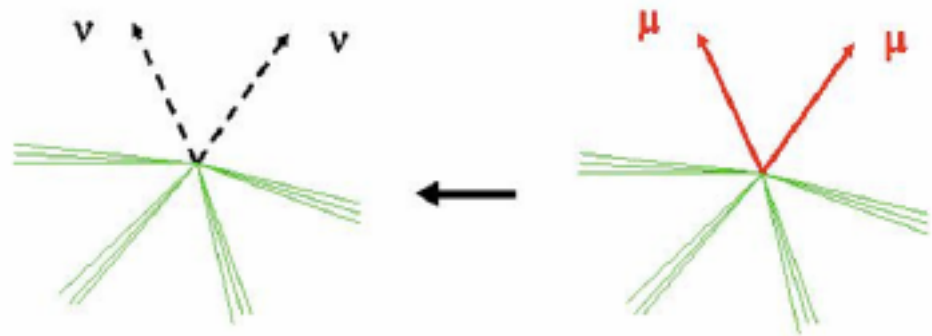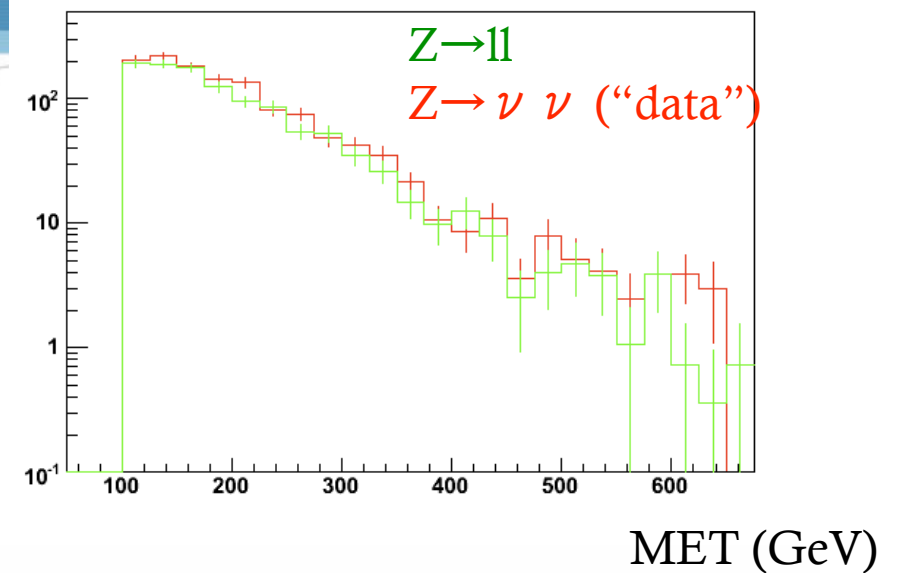
# Z + jet / W + jet

- Discovery of top as 'anomalous' W +4 jet bin contribution

- Measurement of ratio reduces common systematics:
  - Luminosity, PDF, jet energy scale all partially cancel in ratio

- Ratio is a simultaneous test of EW/QCD theory as well as search for anomalous production in either channel (Higgs, SUSY, technicolor)

$$R^{\mu}_{W,Z} = \frac{\sigma(W(\to \mu\nu+ \geq 2\text{jets}))}{\sigma(Z(\to \mu\mu+ \geq 2\text{jets}))} \approx 6.58(6.99)^{\#}$$

$$\frac{\sigma(Z(\to \mu\mu+ \geq 2\text{jets}))}{\sigma(Z(\to \mu\mu+ \geq 3\text{jets}))} \approx 2.3 \quad \text{PYTHIA+CMS}$$

$$\frac{\sigma(Z(\to \mu\mu+ \geq 2\text{jets}))}{\sigma(Z(\to \mu\mu+ \geq 3\text{jets}))} \approx 3.8 \quad \text{ALPGEN+ PYTHIA(+CKKW) + CMS}$$

Illustration of σ vs. $N_{jet}$ measurement at CMS

Z+jets ALPGEN205+Pythia6.335+CKKW matching

Slope -1.245e-00

CMS

Slope=-1.245

$$\sigma(pp \to W/Z + Jets) \propto \alpha_s^n$$

$$R = \frac{dN_{events}}{dN_{jets}} = \frac{\mathcal{L}d\sigma}{dN_{jets}}$$

Inclusive Z+jets cross section (pb)

$N_{jet}$

# Prospects for 100 pb⁻¹

- Quick Study – normalize previous results at 14 TeV to 10 TeV via MCFM calculation

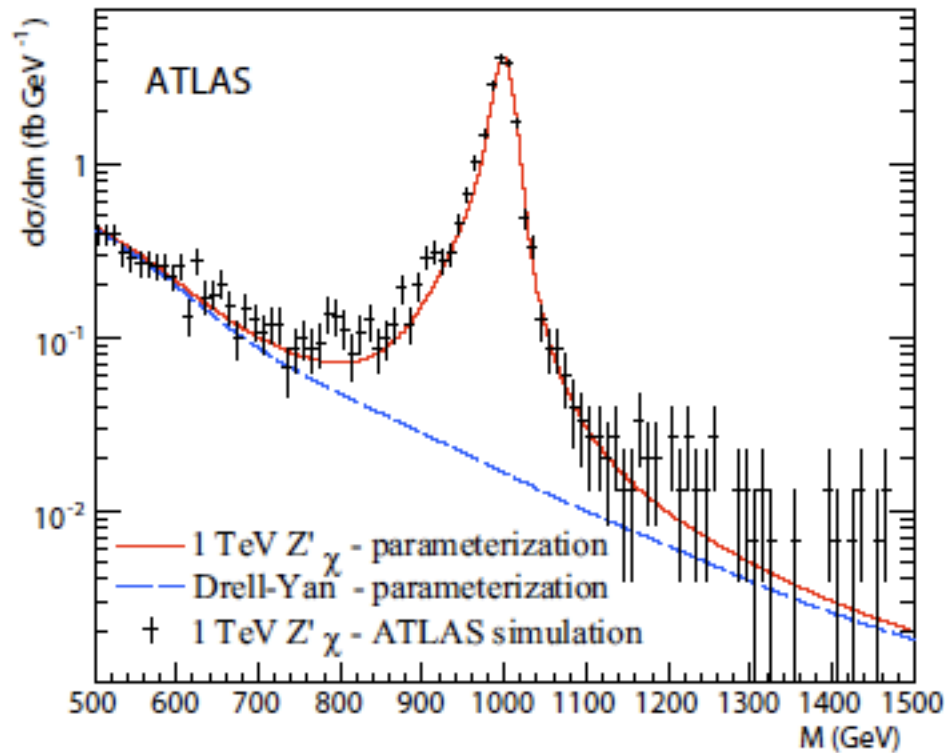- Note cut at jet pt > 40 GeV to lessen sensitivity to jet energy scale corrections
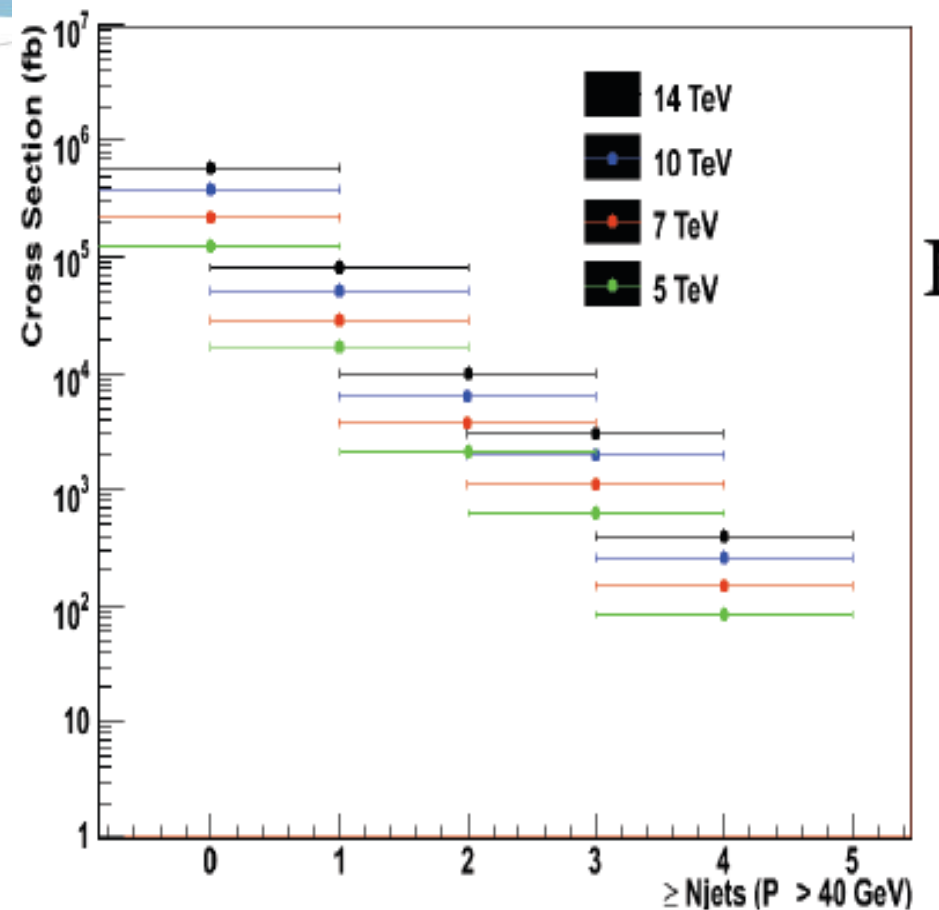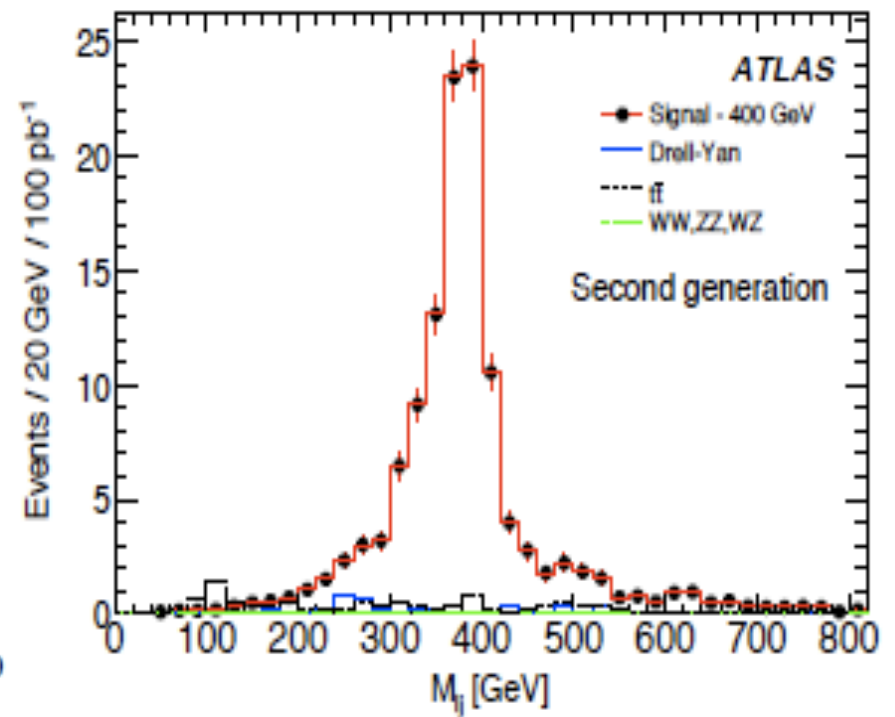
# Prospects for 100 pb⁻¹

- Ultimate goal for Jet Energy Scale (JES ~1 %)
  - First analysis likely to have uncertainty ~10%

- Error on cross-section grows with jet multiplicity
  - On the order of 20% for 2 jet bin assuming 10%
  - On order of 40% for 4 jet bin assuming 10% uncertainty
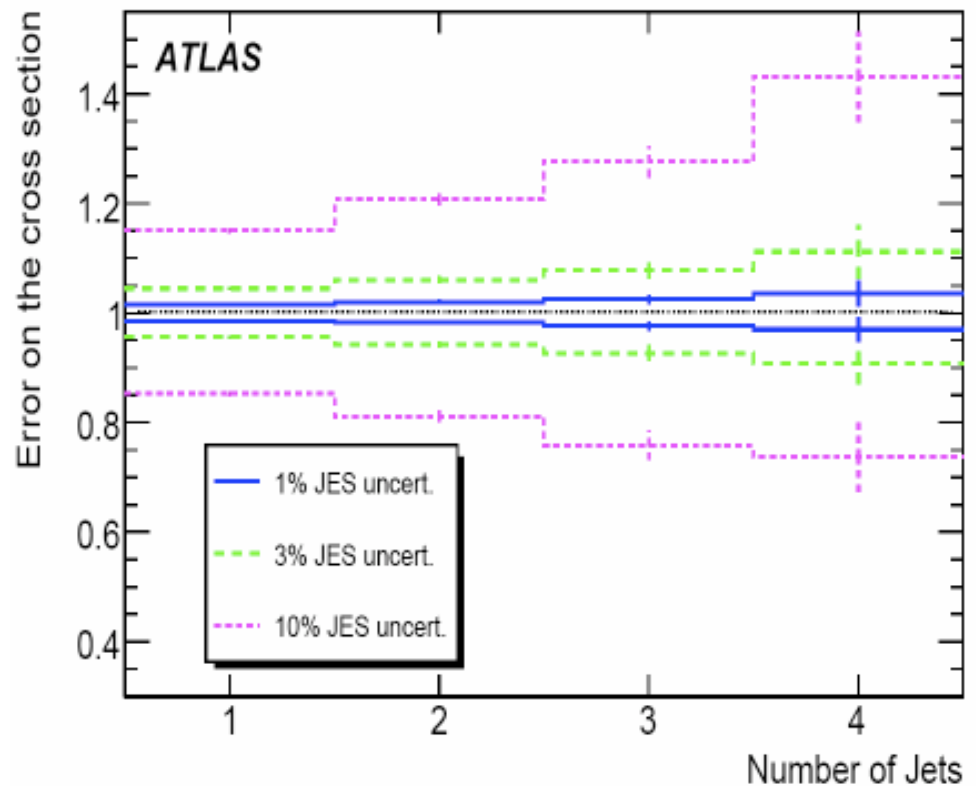
# My Dream…



New heavy gauge bosons…
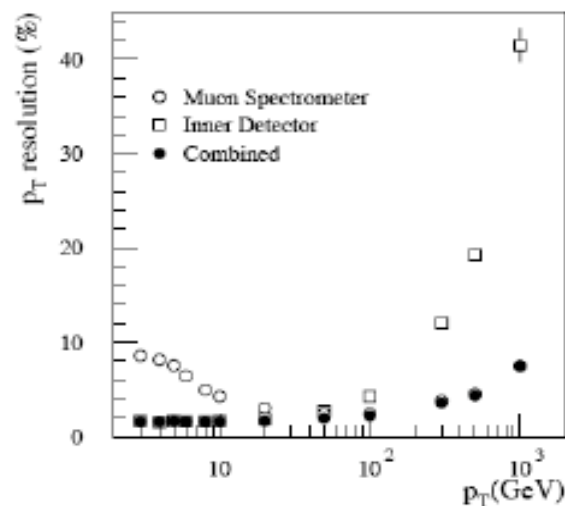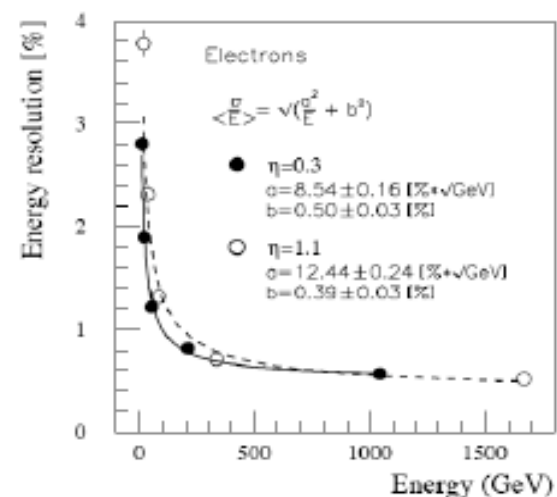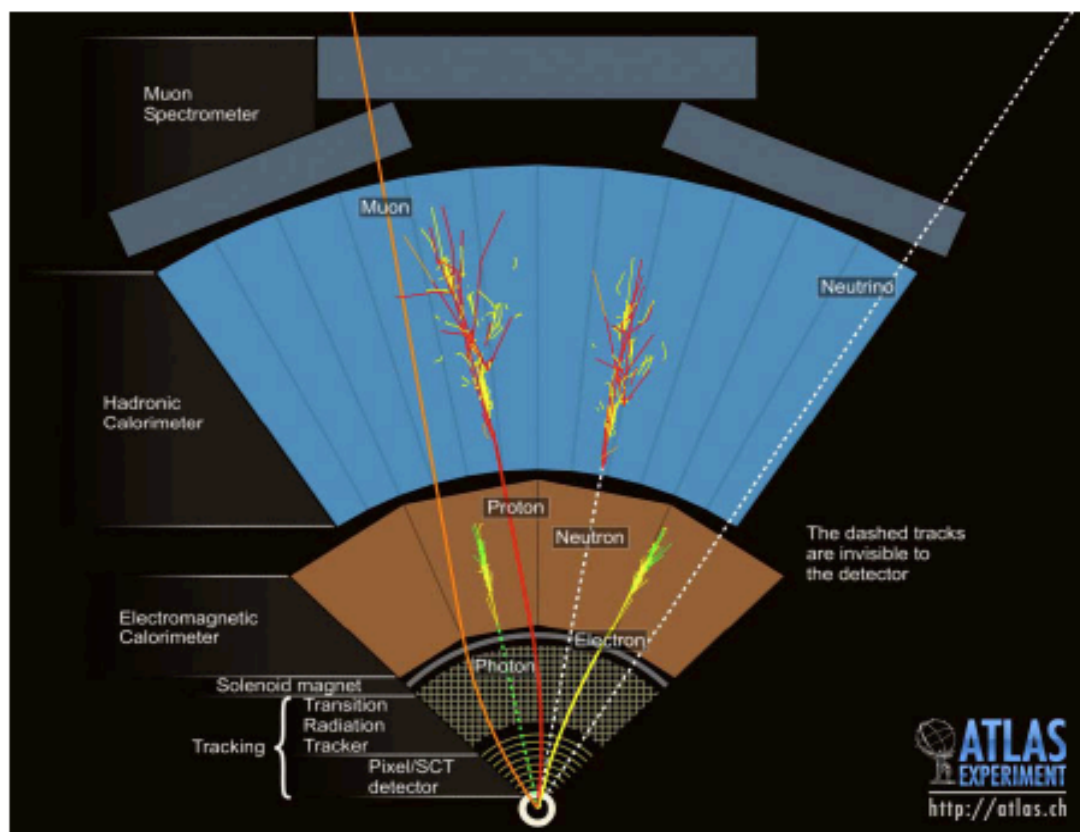


Leptoquarks..

# Summary

- W/Z + jets  good source of calibration (high pt leptons + jets)

- W/Z + jets allows for tests of EW/QCD theory

- W/Z + jets important background for both SM + BSM physics

# Backup

| ATLAS | Expected performance day-1 |
|---|---|
| ECAL uniformity | 1-2% (~0.5% locally) |
| e/γ E-scale | ~ 2 % |
| HCAL uniformity | ~ 3 % |
| Jet E-scale | < 10% |
| Tracking alignment | 10-200 μm in Rφ Pixels/SCT |
| Muon alignment | ~ 1 mm |

# Notes on Underlying Event
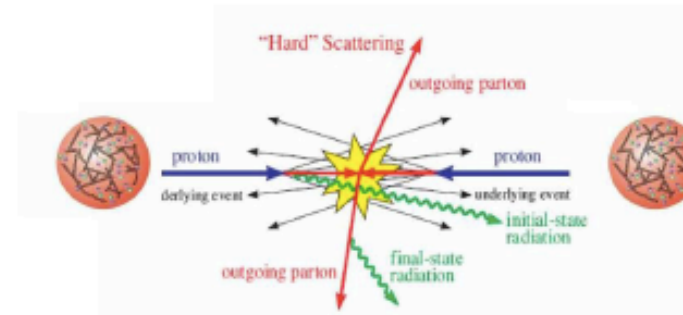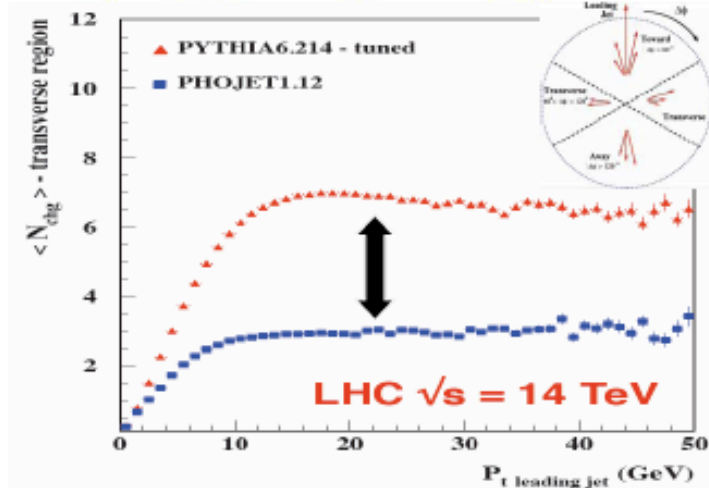




This is a clear unknown at LHC energies
- Dependence with physics process
- How "hard" will be ?